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Structure and Dynamics of the Coronal Magnetic Field

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Magnetic loops and arcades, and helmet streamers are observed to dominate the structure of the solar corona; they are formed by the interaction of photospheric convection and the solar wind with coronal magnetic fields, respectively. We have continued to simulate these interactions in three dimensions using the magnetohydrodynamic (MHD) equations. We have investigated the most promising model for the magnetic heating of the solar corona, the formation of coronal loops by vortex convection, and the structure of active-region magnetic fields consistent with vector magnetograms. In addition, we have determined the equilibrium 3-D structure of magnetic arcades and streamers in spherical symmetry, constructed dynamically from magnetogram fields and a model solar wind, and have compared the resulting density structures with eclipse and coronagraph images, and have demonstrated the mechanism of their eruption into coronal mass ejections (Hundhausen 1993, Linker and Mikić 1995). Finally, we have devised and tested a dynamic three-fluid model of the solar wind.

The question of the mechanism for coronal heating is a classic problem of solar and stellar physics. One main line of study of this question is devoted to the Parker (1983) model, wherein the moderate-scale, slow, random, convective, surface twisting of the footpoints of a magnetic loop leads to fine-scale ohmic dissipation in the atmosphere. We have concentrated on a 3-D MHD representation of this model and on the contribution of magnetic reconnection (resistive tearing) to the dissipation. To do so, we have developed a new diagnostic for 3-D reconnection (Van Hoven, Hendrix and Schnack 1995) and have examined the dynamics of dissipation events.

These studies have led to the following preliminary scenario of how the process operates: 1) random, long-wavelength, field-footpoint (boundary) motions drive a nonlinear cascade in the plasma volume which produces fine-scale current-density sheet filaments (van Ballegooijen 1986, Mikić *et al.* 1989, Schnack and Mikić 1994); 2) at a certain point in this process the current sheets become thin enough (as compared to their widths, see Fig. 1 (b,c)) to become unstable to magnetic tearing/reconnection; 3) this dynamic process further filaments the current density, leading nonlinearly to an extended turbulent (apparently steeper than Kolmogorov) spectrum, as shown in Fig. 1 (a) (Hendrix and Van Hoven 1995, in draft); and 4) The ohmic heating rate is thereby enhanced, over what would arise from the more broadly distributed currents that are driven by solar convection, allowing the dissipation to rise sufficiently to match the input Poynting flux. A manuscript on the overall picture is in draft (Schnack, Mikić and Hendrix 1995).

Solar coronal loops have excited great interest since the *Skylab* era and have reappeared as a prominent feature of the *Yokhoh* (Klimchuk *et al.* 1992) observations. Two limiting models for the formation of a simple, isolated, magnetic loop can be conceived. Either they erupt/emerge with substantial twist from below the convective solar photosphere, or they appear in a nearly unstressed (current-free) state, and are then twisted by differential or vortical flows in the solar surface (any situation between these limits is also possible).

We have begun our simulation study with the latter model, and have succeeded in forming force-free equilibrium loops (Van Hoven, Mok and Mikić 1995), as shown in Fig. 2(a). The applied photospheric twist propagates into the corona, causing parallel current to flow along an S-shaped loop. This appearance has been known from force-free-field models, including those based on observations (McClymont & Mikić 1994). The loop in Fig. 2(a), with a twist of 2.82π on the central field line, is in a force-free equilibrium state. The twisted field lines in the loop are surrounded by overlying field lines that remain relatively undistorted.

It is known that coronal loops can become unstable to kink instabilities if they are twisted sufficiently (Mikić *et al.* 1990). Furthermore, they may exhibit magnetic nonequilibirum that would make them erupt. When a loop with an overlying current-free arcade field is twisted beyond the amount described in the previous section, it undergoes magnetic reconnection with the arcade at the apex, as shown in Fig. 2(b). Shibata (1995) has proposed that this reconnection could be a trigger for loop flares and their outflow jets, a topic that we are presently studying. The dynamic evolution of loops without an overlying magnetic field will be considered in the next grant period.

In order to model the alternative loop-formation mechanism, flux emergence in active regions, we have developed a three-dimensional model. As a first test, we have emerged an untwisted loop underneath, and at right angles to, an existing potential (untwisted) loop. The field lines in the emerging loop reconnect with the magnetic field lines in the existing loop, releasing energy. Finally, we have emerged a twisted loop under an existing twisted coronal loop. The existing coronal loop was first formed by twisting the footpoints of a potential coronal loop (as described above). Next, a twisted flux loop was emerged underneath this coronal loop by specifying the appropriate tangential electric field. The two loops eventually interact and reconnect to reach a lower energy state, producing fast flows. Although these results are preliminary, they are typical of observations of jet flows near emerging flux regions (Shibata 1995).

To create a realistic model of the large-scale magnetic structure of the corona, we have used the field that is observed at the Sun's surface (deduced from daily Wilcox Solar Observatory magnetograms) as input, in combination with specified density and temperature profiles at the surface. A self-consistent 3-D solar-wind solution (Parker 1963) is then developed by integrating the MHD equations in time to steady state. The solution shows the structure of active regions and helmet streamers, regions with closed magnetic fields that trap the coronal plasma flowing out of the Sun.

Such solutions can reproduce the observed structures that are seen in coronagraph images and eclipse photographs of the corona, as shown in Figure 3. The top left panel shows an eclipse image taken on November 3, 1994 by a HAO expedition to Putre, Chile. The top right image is from the Lockheed soft-X-ray telescope on board the Yohkoh spacecraft. The bottom left image shows the polarization brightness *predicted* by the MHD solution, while the bottom right image shows tracings of the magnetic field lines computed from the model. In the bottom images, the color map on the disk shows the magnitude of the magnetic field strength.

This model also allows us to determine the position of the heliospheric current sheet more accurately than has been possible previously. Such a capability can be used to interpret spacecraft measurements of the solar wind. For example, when *Ulysses* was at heliographic latitude 30° S in May 1993, it did not observe the sector-boundary crossing that was expected from a source-surface model prediction of the heliospheric current-sheet position; our model solution shows that the current sheet was confined to lower latitudes than the source-surface model predicted, and is therefore consistent with the observations.

It has long been observed, and confirmed by *Ulysses*, that the temperatures and velocities of the primary constituents of the wind (electrons, protons and helium ions) are often different. In addition, the properties of high-speed (coronal-hole) and low-speed (inter-streamer) solar wind are profoundly distinct. We have constructed a one-dimensional, time-dependent, three-fluid (electrons, protons, and alphas) model of the solar wind. The model has been tested against the static three-fluid results of Bürgi (1992) and code has been used to achieve a variety of steady-state solar-wind solutions arising from different sets of initial and boundary conditions. Our results indicate that flux-tube geometry plays a very important role in the dynamics of the solar wind. The sensitivity of the Coulomb coupling terms to temperature and density implies that the properties of the wind are sensitive to flux-tube geometry: fast *uncoupled* winds (alphas dragging behind protons) arise in faster-than-radial expansion tubes; slow *coupled* winds arise in slower-than-radial expansion tubes. Since recent Ulysses observations show all ions at high speeds in the former case, we infer that the heating of the solar wind must also involve direct heating and/or momentum inputs to the ions, specifically the alphas, in order to accelerate all three, essentially uncoupled, fluids (Ruden *et al.* 1995).

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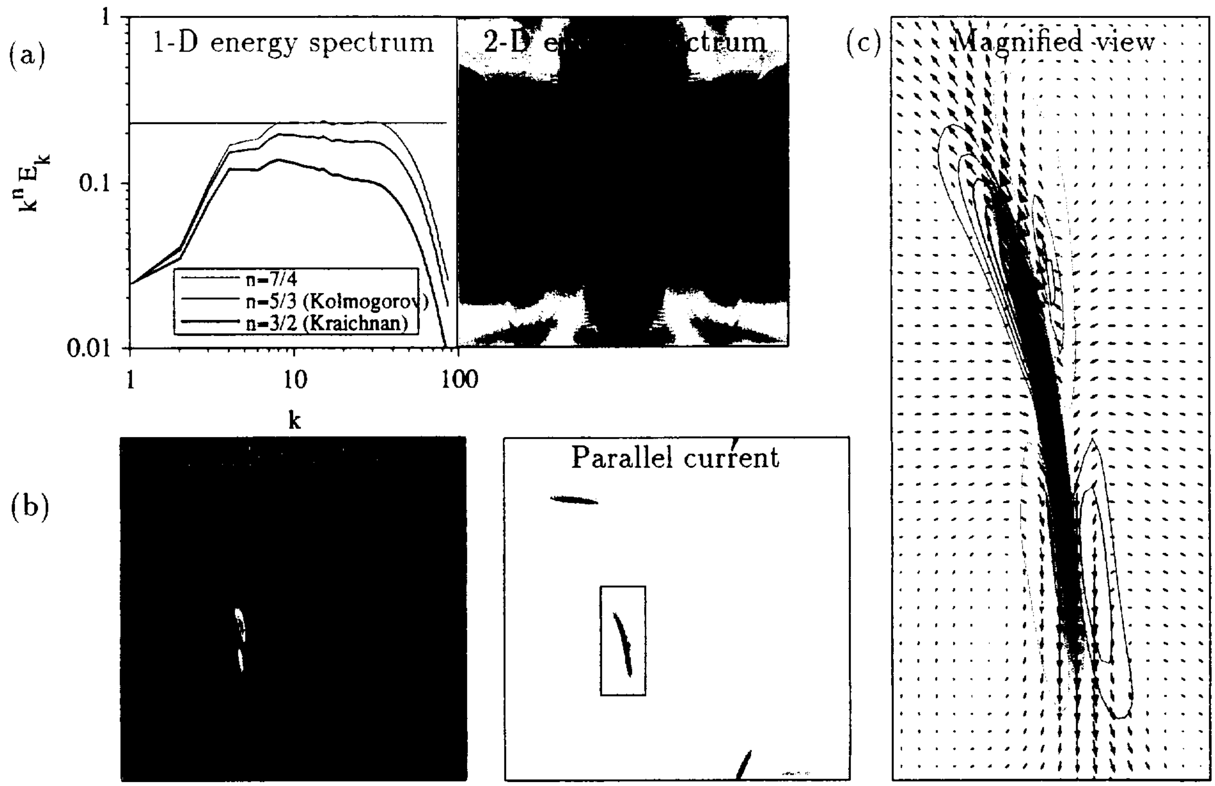


Figure 1. 3-D simulation results from Parker's model at a reconnection/dissipation peak. Energy spectra (a) illustrate a 1-D inertial range and the anisotropy of the 2-D spectrum during current sheet formation. The parallel vorticity and current density are shown in (b) as perpendicular slices through the midplane of the domain. The magnified view (c) also illustrates the local velocity field (vectors) characteristic of reconnection.

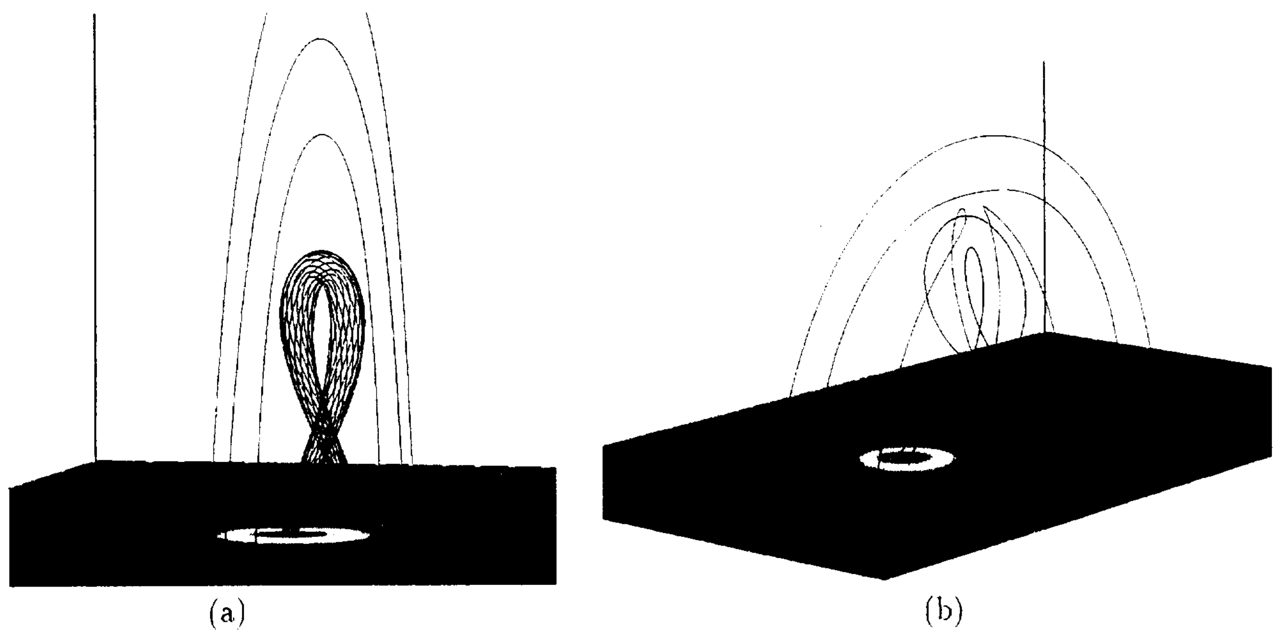
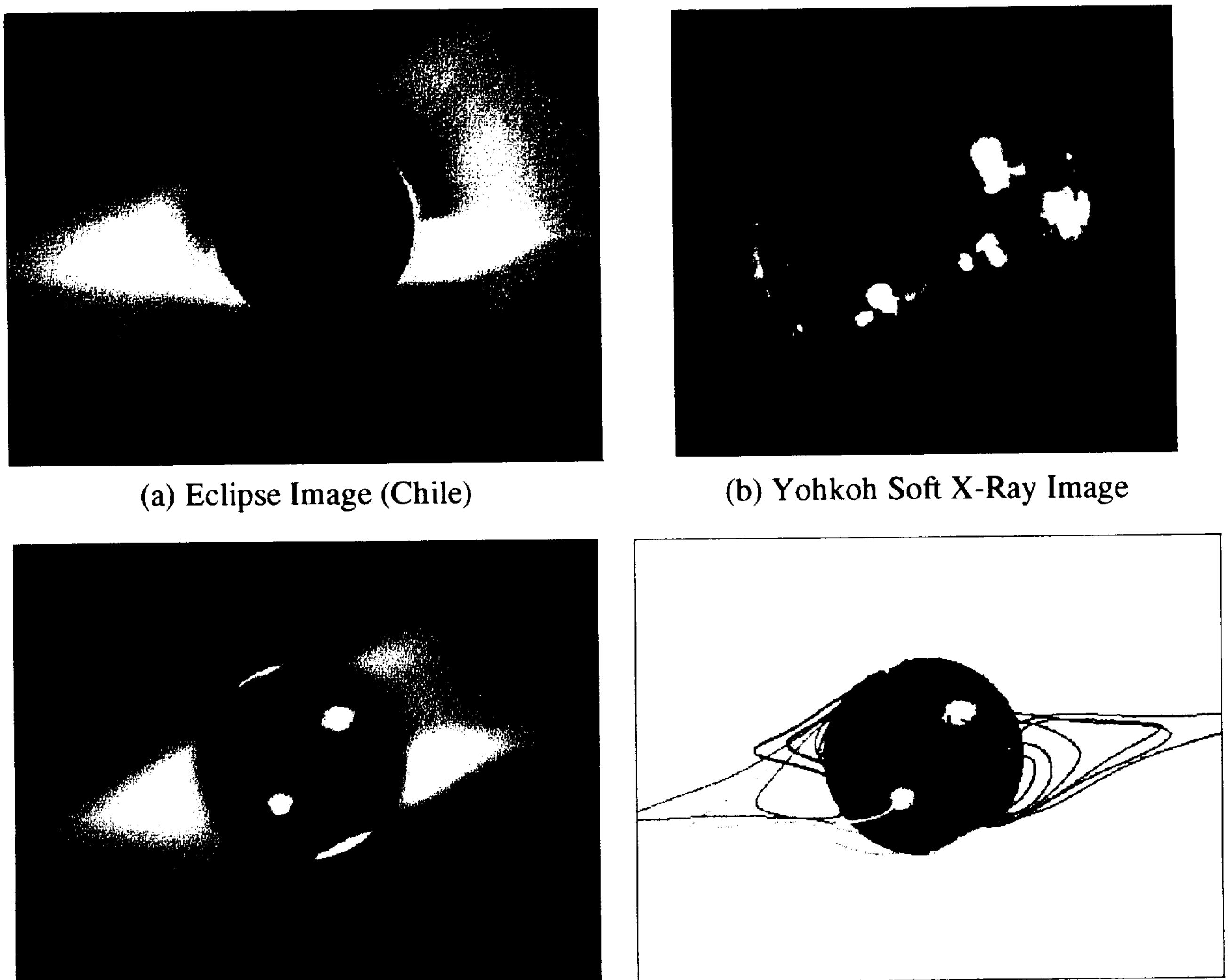


Figure 2. A coronal loop, formed by vortical photospheric motions, in the presence of an overlying arcade field. (a) A stable equilibrium loop with 2.8π magnetic twist. (b) The result of a dynamic reconnection interaction at 4.2π twist, between the loop and arcade fields.

November 3, 1994 Solar Eclipse



(a) Eclipse Image (Chile)

(b) Yohkoh Soft X-Ray Image

(c) Polarization Brightness (MHD Model)

(d) Magnetic Field Lines

Figure 3. A comparison with observations of the diagnostic outputs of a 3-D MHD model. Panel (a) shows the white-light image of the 11/3/94 eclipse taken in Putre, Chile. Panel (b) shows a Yohkoh soft-x-ray image (active regions are bright) taken a few hours earlier. Panel (d) shows the surface magnetic field (strong fields are bright) from a series of Wilcox Observatory magnetograms, along with the coronal field, coexisting with the solar wind, from our MHD model; the traces of the magnetic field show the streamer belt (closed field lines, higher densities) and coronal holes (open field lines, lower densities). Panel (c) shows the polarization brightness predicted, from the densities computed in this model, for comparison with Panel (a).